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(54) **NMR probe with two pairs of counter-wound RF spiral coils inducing a reduced external electric field**

NMR-Probenkopf mit zwei Paaren entgegengesetzt gewundener RF-Spiralspulen zur Reduktion eines externen elektrischen Felds

Sonde RMN avec deux paires de bobines en forme de spirales enroulées à sens contraires induisant un champ électrique externe réduit

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(73) Proprietor: **Agilent Technologies, Inc.
Santa Clara, CA 95051 (US)**

(72) Inventors:
• **Withers, Richard S.
Sunnyvale, CA 94086 (US)**

• **Nast, Robert E.
Saratoga, CA 95070 (US)**
• **Anderson, Weston A.
Palo Alto, CA 94306 (US)**

(74) Representative: **Zimmermann, Tankred Klaus
Schoppe, Zimmermann, Stöckeler & Zinkler
Patentanwälte
Postfach 246
82043 Pullach bei München (DE)**

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Description

FIELD OF THE INVENTION

[0001] This invention relates to nuclear magnetic resonance (NMR) and in particular to RF probe coil geometries that provide a strong RF magnetic field with a minimum of RF electric field over the sample volume.

BACKGROUND OF THE INVENTION

[0002] NMR is a powerful technique for analyzing molecular structure. However it is also an insensitive technique compared to others for structure determination. To gain maximum sensitivity, NMR magnets and spectrometers are designed to operate at high magnetic field strengths, employ low noise preamplifiers and RF probe coils that operate at cryogenic temperatures using cold normal metal transmit/receive coils or preferably superconducting (HTS) materials. The transmit/receive coils are the probe coils that stimulate the nuclei and detect the NMR response from the sample, and therefore are placed very close to the sample to provide high sensitivity. The HTS coils have the highest quality factor, Q , and yield the best sensitivity. Multi-turn spiral coils are commonly used to detect the NMR signal, particularly for lower gamma nuclei such as ^{13}C , ^{15}N and ^{31}P . The electric fields from the turns of the spiral coils near the sample may penetrate the sample and cause dielectric losses and increased noise. The electric fields penetrating the sample also cause detuning of the coil and a resonant frequency that is a function of the dielectric constant and position of the sample. In spinning samples, this detuning can lead to spurious spinning sidebands.

[0003] When the RF current flows through the windings of the NMR probe coil, an RF magnetic field is produced in the sample region that stimulates the resonance in the sample. This RF magnetic field, $\mathbf{B}$, has an associated RF electric field, $\mathbf{E}$. This RF electric field, $\mathbf{E}$, can be calculated utilizing the Maxwell equation:

$$\text{curl } \mathbf{E} = - \text{dB}/\text{dt}.$$

[0004] To minimize losses from this RF electric field, NMR probes are designed so that the sample is in a region where this RF electric field is a minimum, or passes through zero.

[0005] There is another component of electric field that is caused by the electric potential between the windings of an RF coil. This, so-called, conservative electric field arises from the electric potential differences of the turns of the RF coil winding. This component of electric field, $\mathbf{E}_c$, obeys the condition:

$$\text{curl } \mathbf{E}_c = 0.$$

[0006] It is called an electrostatic field since it does not require any time derivatives to produce it. When this component of electric field penetrates the sample or sample tube it can cause energy losses. During transmit and during spin decoupling experiments these losses can cause undesired heating of the sample. During the receive phase, the currents induced by the NMR signal also produce an electric potential between turns of the RF probe coil, causing electric fields to penetrate the sample volume resulting in a loss of Q and reduced sensitivity. Since the sample is usually at or near room temperature and the probe coil is at a very low temperature, noise power is also introduced into the RF probe coil through this electric field coupling. This loss is proportional to the electric field coupling between the sample and the RF probe coil and depends upon the dielectric loss tangent or dissipation factor of the sample and sample tube material and the electrical conductivity of ionic samples.

[0007] Small changes in the strength or direction of the DC magnetic field applied to the probe or other magnetic field fluctuations induce small shielding currents in the surface of the superconductor films of the spiral coils. These shielding currents can cause magnetic field inhomogeneity in the sample region resulting in line broadening and loss of NMR sensitivity. (US Patent 5, 565, 778). To reduce the shielding currents the coil turns may be slit in the direction parallel to that of the RF current flow thereby reducing size of the shielding current loops. Each turn of the spiral coil may be split into a number of parallel conductors or "fingerlets" with a small insulating gap between fingerlets.

[0008] Electrostatic shields have been used in the prior art to reduce this electric field. (US Patent Publication No. 2008/0150536). The task of reducing the electric field in the region of the sample is very important, and therefore there is a need to find an alternative method and apparatus. Existing technology does not utilize the counter-wound spiral coils to minimize the electric field in the region of the sample.

[0009] Spiral wound coils have been used before as a surface coil for MRI measurements when it was desired to keep the coil small, and yet be able to tune it to a low frequency (US Patent 5, 276, 398). It was proposed to use a pair of circular counter-wound coils with capacitive coupling between them for MRI applications to achieve a lower resonant frequency than could be achieved with a single coil. The teaching of this art did not consider or contemplate reducing the electric field over the sample region.

[0010] RF coils for high resolution NMR probes must be precisely tuned to the NMR resonant frequency of the nucleus being studied. For maximum sensitivity the electric field from the probe RF coils must produce a minimum electric field in the sample region. The coils are tuned to

resonate in the RF frequency range of the nuclear species being studied. The probe is tuned by adjusting the total coil length of wire used to wind the coils. Fine tuning is provided by a variable capacitor or by a wand that provides small adjustable changes to the resonator inductance.

[0011] US 2005/0088179 A1 suggests an MRI coil assembly having two RF spiral coil sets, each set having one clockwise wound main coil and one counterclockwise wound auxiliary coil. The purpose of the counterwound auxiliary coils is to homogenize the magnetic field intensity of the spiral main coils along an axis running through the center of and perpendicular to the spiral coils. The auxiliary coils are placed axially more distant to the sample region than the main coils.

[0012] Therefore there is a need in providing the RF probe coils of certain geometries, which are characterized by a strong RF magnetic field with substantially reduced RF electric field over the sample volume.

SUMMARY OF THE INVENTION

[0013] The invention is defined in claims 1 and 7, respectively. Particular embodiments are set out in the dependent claims.

The present invention provides an NMR probe coil that allows for producing lower electric field components over an NMR sample region. The NMR probe incorporates two sets of counter-wound spiral coil pairs. Each pair of spiral coils are wound on opposite sides of a sample region, with both spirals having a rectangular or oval shape to match that of the desired active sample volume. Two sets of counter-wound spiral coils are used, one on each side of the sample. The two spiral coils of each set are counter-wound, i.e. the two coils are wound in opposite directions, one being wound clockwise and the other counter clockwise when moving from inside the spiral to the outside. The two sets of coil pairs are driven from a common coupling loop. In its lowest mode of resonance, the current flow in the four spiral coils will be in the same angular direction at a given moment of time, producing a large RF magnetic field in the sample volume adjacent to the coils. As a result of the opposite "handedness," of each coil of a set, the electric potential will be negative on the inside of one spiral and positive on its outside, while the potential on the other spiral coil of the set will be positive on its inside and negative on its outside. By adjusting the relative length of each coil of a spiral coil pair, the electric field from one spiral coil of a pair can produce an equal-but-opposite spatial distribution of potential, resulting in an electric field that is well confined to the dielectric-filled space between the spirals and minimizing the electric field in the sample region.

[0014] The relative strength of the electric field from each spiral coil is sensitive to the coil length. The electric fields are oppositely directed in the sample region. Thus the relative electric field strength of each coil of a spiral coil pair may be adjusted by changing the relative length

of each spiral coil to minimize the electric field strength in the sample region. The lowest resonant frequency of a spiral coil pair also depends upon the total length of the two spiral coils. Starting with a sufficient winding length, the ends of the spiral coils may be selectively cut to simultaneously tune the coil pair to the desired NMR frequency and at the same time reduce the external electric field in the sample region produced by the counterwound spiral coil pair.

[0015] HTS coils are normally adjusted using a laser trimmer to make the cut. In some configurations of counter-wound spiral coil pairs the coil ends may overlap causing difficulties when attempting to tune the individual coils by laser trimming. When cutting a turn or fingerlet of the coil, the laser beam may also pass through the substrate to the coil on the other side making a destructive cut in this coil. To overcome this problem, a material that adsorbs or scatters the laser beam is introduced between the two coils of the counter-wound coil pair.

[0016] It is preferable to cut all of the fingerlets across the coil turn when being trimmed for adjusting the winding length of it. If some of the fingerlets are cut and other adjacent fingerlets of the same turn are not cut and having shorter ends, an arc may occur between the shorter end fingerlet and a neighboring fingerlet, when transmitted power is applied to the coil. To prevent such an occurrence, the entire shorter end fingerlet may be removed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The forgoing aspects and advantages of the present invention will become better understood by reference to the following detailed description when taken in conjunction with the accompanying drawings.

[0018] Fig. 1A is a view of a prior art HTS NMR probe coil fixed to a dielectric substrate.

[0019] Fig. 1B is an illustration of fingerlets of HTS coils.

[0020] Fig. 2A is a view of the first spiral coil of a spiral wound coil pair.

[0021] Fig. 2B is a view of the second spiral coil of the spiral wound coil pair when seen from the same direction as the first spiral coil of Fig. 2A.

[0022] Fig. 2C is a view of the two coils of a spiral wound coil pair as seen from the face of the coil pair, illustrating the counter-wound feature of the two coils.

[0023] Fig. 3A-E are sections A-A of Fig. 2C illustrating various coil arrangements according to different aspects of the invention.

[0024] Fig. 4 is a block diagram depicting a cryogenically cooled NMR probe utilizing two sets of counterwound spiral coil pairs of the subject invention.

[0025] Fig. 5A is a view of the first spiral coil of a spiral wound coil pair fixed to the outside surface of a cylindrical dielectric member.

[0026] Fig. 5B is a view of the second spiral coil of a spiral wound coil pair fixed to the inside surface of the same cylindrical dielectric member shown in Fig 5A.

[0027] Fig. 6 is a view of two sets of spiral wound coil pairs showing only the spiral wound coils fixed to the outside surface a cylindrical dielectric member.

[0028] Fig. 7A is a view of two sets of counter-wound spiral coil pairs, with one coil of each set fixed to the outside surfaces of an outer cylindrical dielectric member and the second coil of each set fixed to the outer surface of a co-axial inner cylindrical dielectric member.

[0029] Fig. 7B is a view with the two cylinders of Fig. 7A fixed in final position.

DETAILED DESCRIPTION OF THE INVENTION

[0030] In this work the embodiments are disclosed for HTS probe coils, cooled normal metal coils, and room temperature NMR probe coils. Contemporary HTS coils need to be cooled as they lose their superconducting properties at room temperature. The coils made of normal metal may be cooled or operated near room temperature.

[0031] Fig. 1A depicts a prior art HTS NMR probe coil assembly **100** that provides the RF field to the sample thereby stimulating the nuclear spins and then receiving the response of the nuclear spins in the sample. Typically the coil winding **102** is composed of a high temperature superconducting (HTS) material such as yttrium barium copper oxide (YBCO). The HTS material may be sputtered, evaporated, or otherwise deposited upon an electrically insulating planar substrate **101** such as sapphire. Typically the supporting substrate may be 400 micrometers thick and the HTS material 0.3 micrometers thick. Each turn of the coil may be composed of a number of parallel channels, or "fingerlets" of the HTS material. The section enclosed by box **103** is enlarged and displayed in box **103'** of Fig. 1B.

[0032] Fig. 1B depicts how each turn of coil **102** is split into a number of parallel conductors or fingerlets **107**. The spacing between adjacent turns, **105**, is typically in the range of 30 to 100 micrometers. The purpose of the fingerlets is to prevent any external magnetic fields from inducing small persistent current loops in the windings causing the distortion of the magnetic field homogeneity over the sample region. The spacing between fingerlets, **107** may be in the range of 10 micrometers and the width of each fingerlet in the range 0 to 20 micrometers.

[0033] For NMR applications two probe coils are used, one on each side of the sample tube. The substrate supporting each coil is attached to the heat exchanger in region **106** (Fig. 1A). The heat exchanger (**143** shown in Fig. 4) provides the cooling and temperature control of probe coil assemblies **100**. A coupling loop (**154** of Fig. 4) is inductively coupled to the coil windings and is electrically connected to the NMR spectrometer. It couples the RF energy to the coil to excite NMR resonance and it receives the response induced into the coil from the sample material and transmits it to the spectrometer for processing, recording and display.

[0034] In the HTS NMR probe the sample tube is typ-

ically a cylindrical tube with the long axis of the tube parallel to each face of the planar substrates **101**. The sample tube passes very close to the coil windings **102** in the regions indicated by the dotted boxes **108** of Fig. 1A. In this region the potential differences between adjacent and nearby windings produce electric fields that penetrate the nearby sample tube and NMR sample causing energy loss and a reduction of sensitivity as described above.

[0035] Fig. 2A and 2B depicts the two spiral wound coils that form a spiral counter-wound coil pair. In operation, the two coils of the coil pair are placed on opposite sides of dielectric substrate **111**. Spiral coil **112** of Fig. 2A formed on dielectric substrate **111** and is wound counter-clockwise starting from the inside end **113** to the outer end **114**. Spiral coil **122** of Fig. 2B formed on dielectric substrate **121** and is wound clockwise starting from the inside end **123** to the outer end **124**.

[0036] Fig. 2C depicts a front view with the two spiral counter-wound coils **112** and **122** in place adjacent to each other with turns closely aligned, with coil **112** forming a counter-clockwise and coil **122** forming a clockwise spiral moving from the inside ends to the outside ends. The two coils may be clamped or glued together to give a monolithic structure. Each of the coils, **112** and **122** may be composed of a number of fingerlets, typically between 4 and 30 fingerlets per turn. Breaking the coil into a number of fingerlets reduces any magnetization induced in the turns by external magnetic fields.

[0037] In a preferred embodiment an additional laser light blocking material is placed between coils **112** and **122**. In one embodiment the light blocking material is placed in the region outlined by dotted line **133** of Fig. 2C. The light blocking material should cover the region where either inner coil ends, **113** and **123**, or the outer coil ends **114** and **124**, or both, are located. This may be at the top of the coil as illustrated in Fig. 2C, or where ever the ends of the coil are located, which may be on the bottom or a side of the coils.

[0038] When trimming the coil **112** to adjust the external electric field or the resonant frequency of the coil pair, the light blocking material in region **133** prevents light from the laser trimmer against cutting parts of coil **122** that is located directly behind the region on coil **112** that is being trimmed. Conversely when trimming coil **122**, the light blocking material prevents parts of coil **112** from being damaged.

[0039] Fig. 3A, 3B, 3C, 3F illustrate different spiral coil and substrate arrangements that provide low external electric fields according to the subject invention. They correspond to various coil and dielectric substrate arrangements that give the counter-wound spiral coil pairs a low external electric field. They all have the same projection as seen in Fig. 2C and correspond to different coil/substrate arrangements as seen when viewed by taking a cross section cut A-A through Fig. 2C.

[0040] In Fig. 3A substrate **121** with coil **122** of Fig. 2B are clamped or glued directly to the back of substrate

111 spiral coil **112** of Fig. 2A. These spiral coils may be laser trimmed while they are separated, and then clamped together in their final configuration when checking their frequency and external electric field. When mounting a set of two of these pairs in a probe, the preferred coil orientation is with the substrate face supporting a coil to be placed closest to the sample. It is also preferred that the two coils nearest the sample tube have the same "handedness".

[0041] In section A-A of Fig. 3B spiral coil **122** is formed directly on the second side of substrate **111**, of Fig. 2A with its spiral coil **112** on the first side of substrate **111**. This arrangement provides a very rugged and compact counter-wound spiral coil pair. For coils directly bonded to the two sides of the same substrate a suitable dielectric substrate material must be chosen. When using HTS coils the dielectric substrate must not only support the coils and have good thermal properties to enable suitable cooling, but must also block the laser light to prevent it from damaging the coil on the opposite side.

[0042] In the arrangements illustrated by Fig. 3C, 3D and 3E, two identical spiral coils are used. The oppositely wound spiral coil are assembled from two identical coils mounted on separate dielectric sheets, with the second sheet rotated by 180 degrees about its vertical axis. If the first coil **112** is wound in a counter-clockwise manner as illustrated in Fig 2A the second coil, when viewed through substrate will be wound clockwise starting from the center in both cases. A separate light blocking material is positioned next between the two spiral coils of a counter-wound pair to prevent laser light from damaging one spiral coil while trimming the other.

[0043] In Fig 3C a dielectric sheet of laser light blocking material **131**, that either absorbs or scatters the laser light, is inserted between the two coils **112** and **112'** in the region indicated by **133** of Fig. 2C. The two substrates **111** and **111'** of Fig. 3C are then glued together, introducing the glue from the edge. Alternatively the two substrates **111** and **111'** may be clamped together. A laser light blocking material **131** that works by scattering the light is 25.4 to 76.2 μm (0.001 to 0.003 inch) thick Teflon® sheet. Epoxy has been found to be an effective glue.

[0044] Fig. 3D illustrates an embodiment with the entire region between the two substrates **111** and **111'** is covered by the laser light blocking material **132** and then clamped or glued.

[0045] Fig. 3E illustrates another alternative arrangement. In this case the two substrates **111** and **111'** are glued or clamped with the coils facing each other. An insulating layer **134** placed between them prevents the coils **112** and **112'** from touching and shorting and provides an optical barrier to the laser light. By choosing material and thickness of insulating layer **134** the capacitance between the two coils may be controlled as well as forming an optical barrier to the laser light.

[0046] In each of these embodiments Fig. 3A through 3E the front projection of the spiral wound coil assembly appear as indicated in Fig. 2C with spiral coil **112** is wound

counterclockwise moving from the inside coil end to the outside end, and spiral coils **122** or **112'** are wound clockwise from inside end to outside end or visa versa.

[0047] If one end of a first coil is located on either the left or right side of the coil (as opposed to the top or bottom of the coil), an counter wound spiral coil may be formed from by a 180 degree rotation about a horizontal axis. The counter wound coil must then be correctly positioned to overlap with the first coil.

[0048] The NMR probe incorporates two sets of these counter wound coil pairs, one set on each side of the sample region illustrated by **130** and **130'** of Fig. 4. Each of the arrangements of Fig. 3A - 3E is a different embodiment of the subject invention.

[0049] Fig. 4 is a block diagram of a cryogenically cooled probe **140** with sample tube **141** and NMR sample **142**. The probe **140** has an outer shell **144** made of non-ferromagnetic material such as aluminum and an inner dielectric tube **145** made of fused quartz, for example.

The outer shell **144** and dielectric inner tube **145** form a vacuum tight space **146**. This space is evacuated providing good thermal insulation of the cold coil pairs **130** and **130'** and the warm sample **142** and sample tube **141**. Two counter wound spiral coil pairs, **130** and **130'** are identical and are mounted on opposite sides of sample tube **141**, and each is in thermal contact with heat exchanger **143**. Heat exchanger **143** surrounds inner tube **145** thereby providing cooling to both coil pairs **130** and **130'**. Cooling for the spiral-wound coils is provided by cold gas source **147**. The HTS counter-wound spiral coil pairs **130** and **130'** are typically cooled to a temperature in the range of 20 K. The cold gas flows to and from heat exchanger **143** by cold gas transfer tubes **148**. The tube supplying the cold gas from cold gas source **147** is thermally insulated from the preamplifier and T/R (Transmit/Receive) switch **149**, while the tube returning the partially spent gas is in thermal contact with the preamplifier and T/R switch **149**, thereby cooling it to a low temperature typically in the range of 80 K. Alternatively two cold gas coupling loops may be used, one to cool the spiral wound coils **130** and one to cool the preamplifier and T/R switch **149**.

[0050] An RF probe cable **150** transmits RF power to the spiral wound coils **130** and **130'** via coupling loop **154** and receives the NMR response signals and transmits them to the preamplifier and T/R switch **149**. The preamplifier and T/R switch receive transmit power from the spectrometer (not shown) via cable **153** and send the amplified NMR signal to the spectrometer (not shown) on cable **151**.

[0051] Fig. 5A illustrates a spiral coil **162** fixed to the outer surface of a cylindrical dielectric coil form **161**. The winding extends from the inside end of the spiral **163** winding clockwise to the outside end **164**. The coil winding is composed of HTS material or a normal metal such as copper or aluminum, in the form wire or preferably thin strip conductors. The strips may be composed of two or more layers of different metals to produce a strip that has

near-zero magnetic susceptibility. The coil may be operated at a low temperature for HTS coils or at room temperature or below room temperature for normal metal coils.

[0052] As illustrated in Fig. 5B, a counter-wound coil **172** is fixed to the inside surface of the same coil form **161** with spiral coil **162** not shown for sake of clarity. This winding extends from the inside end **173** of spiral **172** winding counter clockwise to the outside end **174**. This coil is closely adjacent to coil **162**, which is on the outer surface of coil form **161**. The coil **162** and coil **172** form a counter wound spiral coil pair.

[0053] A second set of a counter wound coil pair is placed on the same coil form, but on the opposite side of coil form **161**. Coil assembly **160** of Fig. 6 is a view of the two coils **162** and **162'** on the outer surface of coil form **161**. Both coils **162** and **162'** have a counter wound coils **172** and **172'** (not shown) on the inside surface of coil form **161**, directly adjacent to coils **162** and **162'** forming two sets of counter-wound spiral coil pairs.

[0054] In operation the coil assembly **160** of Fig. 6 is inductively coupled to the spectrometer in the manner as illustrated in Fig. 4 by coils **130** and **130'**. Final tuning of the coils of assembly **160** is done by machining or mechanically cutting the ends of the individual coils to achieve the correct frequency and potential balance to achieve minimum electrostatic coupling to the sample and sample tube.

[0055] Fig. 7A is an alternative configuration of two sets of counter-wound spiral coil pairs mounted on cylindrical dielectric coil forms **181** and **191**. One coil of each set, **182** and **182'**, is mounted on the outside surface of coil form **181**. The second coil of each set, **192** and **192'**, is mounted on the outside surface of the second coil form **191**. Fig. 7A shows the two dielectric coil forms axially aligned with common axis **185**. When wound, the second coil form, **191**, slides snugly into coil form **181**, with coils **182** and **192** overlapping to form one counter-wound spiral coil set and coils **182'** and **192'** forming the second counter-wound spiral coil set. Fig. 7B illustrates the assembled coil, ready for mounting in the probe. The counter-wound coil pair **182**, **192** is mounted in the position illustrated by **130** of Fig. 4, and the counter-wound coil pair **182'**, **192'** is mounted in the position illustrated by **130'** of Fig. 4. The coils may be tested for their resonant frequency and electric field in the region of the sample tube **141** and sample **142**. Should trimming be needed the coils may be removed and the coil leads cut with a mechanical cut-off tool, a laser cutter, or a scalpel. The coils may then be reassembled for further testing or final installation in a probe.

Claims

1. An NMR probe incorporating two sets of counter-wound RF spiral coil pairs (112, 112', 122; 162, 172; 182, 192) having a sample region therebetween for

exciting and detecting NMR signals from a sample positioned in the sample region, wherein each set of said counter-wound RF spiral coil pairs comprises:

a pair of spiral coils (112, 112', 122; 162, 172; 182, 192), each spiral coil being wound in opposite angular directions relative to each other when moving from an inside (113, 123; 163, 173) of a respective spiral to its outside (114, 124; 164, 174); and
a dielectric member (111, 111', 121; 161; 181, 191) spacing apart said spiral coils (112, 112', 122; 162, 172; 182, 192), wherein said spiral coils are deposited on said dielectric member and arranged on opposing surfaces of said dielectric member,

wherein a length of said spiral coils (112, 112', 122; 162, 172; 182, 192) of said two sets of counter-wound RF spiral coil pairs is adjusted such that an electric field induced within the sample region by electric potential of said spiral coils of said two sets of counter-wound RF spiral coil pairs is reduced, and wherein the two sets of counter-wound RF spiral coil pairs are driven from a common coupling loop (154) and the current flow in the four spiral coils of the two sets of counter-wound RF spiral coil pairs is in the same angular direction at a given moment of time.

2. The NMR probe of claim 1, wherein each said spiral coil (112, 112', 122; 162, 172; 182, 192) of said two sets of counter-wound RF spiral coil pairs is fabricated from HTS material.
3. The NMR probe of claim 1 or 2, wherein said dielectric member (111, 111', 121) for each set of counter-wound RF spiral coil pairs is a planar substrate.
4. The NMR probe of claim 3, wherein said planar substrate (111, 121) for each set of said counter-wound RF spiral coil pairs comprises a laser light blocking material (131, 132, 134) arranged between at least portions of the pair of spiral coils of each set of said counter-wound RF spiral coil pairs.
5. The NMR probe of claim 4, wherein the dielectric members for both sets of counter-wound RF spiral coil pairs are formed by a cylindrical member (161), with said pairs of spiral coils for both sets of counter-wound RF spiral coil pairs disposed thereon and wherein one spiral coil (162) of each said pair is disposed on an outside surface of said cylindrical member (161) and the other spiral coil (172) of each said pair is disposed on an inside surface of said cylindrical member (161).
6. The NMR probe of claim 4, wherein the dielectric

members for both sets of counter-wound RF spiral coil pairs are formed by an outer and an inner coaxial cylindrical member (181, 191) with said pairs of spiral coils (182, 192) for both sets of counter-wound RF spiral coil pairs disposed thereon and wherein one spiral coil (182) of each said pair is disposed on the outside surface of said outer cylindrical member (181) and the other spiral coil (192) of each said pair is disposed on the outside surface of said inner cylindrical member (191).

7. A method of reducing an electric field induced within a sample region by electric potential of two sets of counter-wound RF spiral coil pairs (112, 112', 122; 162, 172; 182, 192) of a NMR probe and tuning them to a resonant frequency of a NMR sample, the method comprising the steps of:

providing two pairs of counter-wound RF spiral coils (112, 112', 122; 162, 172; 182, 192) with said spiral coils of each pair being wound in opposite angular directions relative to each other when moving from an inside of a respective spiral to its outside and being deposited on a dielectric member (111, 111', 121; 161; 181, 191), wherein said spiral coils of each pair are arranged on opposing surfaces of said dielectric member;

placing the pairs of counter-wound spiral coils with said sample region therebetween; driving the two pairs of counter-wound RF spiral coils from a common coupling loop (154), wherein the current flow in the four spiral coils of the two pairs of counter-wound RF spiral coils is in the same angular direction at a given moment of time;

measuring the electric field within the sample region; and

reducing the electric field by adjusting a length of the spiral coils (112, 112', 122; 162, 172; 182, 192) of said two pairs of counter-wound RF spiral coils.

8. The method of claim 7, further comprising the step of manufacturing each said spiral coil of said two sets of counter-wound RF spiral coils (112, 112', 122; 162, 172; 182, 192) from HTS material.

9. The method of claim 7 or 8, wherein the dielectric member (111, 111') is a planar substrate comprising a laser light blocking material (131, 132, 134) between at least portions of the pair of spiral coils of each set of said counter-wound RF spiral coil pairs and each coil (112, 112') of the pair of counter-wound coils is mounted on opposite sides of the planar substrate.

10. The method of claim 7, 8 or 9, further comprising the

step of adjusting the length of at least one spiral coil (112, 112', 122; 162, 172; 182, 192) by cutting the spiral coil utilizing a laser trimmer.

11. The method of claim 7, further comprising the steps of: manufacturing the spiral coils (112, 112', 122; 162, 172; 182, 192) from normal metal, and adjusting the length of at least one spiral coil by cutting the spiral utilizing a scalpel or a mechanical cutoff tool or a laser trimmer.

12. The method of claim 7, 8 or 11, wherein the dielectric members for both pairs of counter-wound RF spiral coils are formed by a cylindrical member (161) having disposed on its outside surface one spiral coil (162) of each said pair and on its inside surface the other spiral coil (172) of each said pair.

13. The method of claim 7, 8 or 11, wherein the dielectric members for both pairs of counter-wound RF spiral coils are formed by an outer and an inner coaxial cylindrical member (181, 191) having one spiral coil (182) of each said pair disposed on an outside surface of the outer cylindrical member (181) and the other spiral coil (192) of each said pair disposed on the outside surface of the inner cylindrical member (191), whereby said coil pairs are straddling the sample region.

Patentansprüche

1. Eine NMR-Sonde, die zwei Sätze von gegenläufig gewickelten RF-Spiralspulenpaaren (112, 112', 122; 162, 172; 182, 192) umfasst, mit einer Probenregion zwischen denselben zum Erregen und Erfassen von NMR-Signalen von einer Probe, die in der Probenregion positioniert ist, wobei jeder Satz der gegenläufig gewickelten RF-Spiralspulenpaare folgende Merkmale aufweist:

ein Paar von Spiralspulen (112, 112', 122; 162, 172; 182, 192), wobei jede Spiralspule in entgegengesetzten Winkelrichtungen relativ zueinander gewickelt ist, wenn sich dieselben von einer Innenseite (113, 123; 163, 173) einer jeweiligen Spirale zu ihrer Außenseite (114, 124; 164, 174) bewegen; und

ein dielektrisches Bauglied (111, 111', 121; 161; 181, 191), das die Spiralspulen (112, 112', 122; 162, 172; 182, 192) voneinander beabstandet, wobei die Spiralspulen auf dem dielektrischen Bauglied aufgebracht sind und auf gegenüberliegenden Oberfläche des dielektrischen Bauglieds angeordnet sind,

wobei eine Länge der Spiralspulen (112, 112', 122; 162, 172; 182, 192) der zwei Sätze von gegenläufig

- gewickelten RF-Spiralspulenpaaren eingestellt ist, sodass ein elektrisches Feld, das durch ein elektrisches Potential der Spiralspulen der zwei Sätze von gegenläufig gewickelten RF-Spiralspulenpaaren in der Probenregion induziert wird, reduziert ist, und wobei die zwei Sätze von gegenläufig gewickelten RF-Spiralspulenpaaren von einer gemeinsamen Kopplungsschleife (154) getrieben werden, und der Stromfluss in den vier Spiralspulen der zwei Sätze von gegenläufig gewickelten RF-Spiralspulenpaaren zu einem bestimmten Zeitpunkt in der gleichen Winkelrichtung ist.
2. Die NMR-Sonde gemäß Anspruch 1, bei der jede der Spiralspulen (112, 112', 122; 162, 172; 182, 192) der zwei Sätze von gegenläufig gewickelten RF-Spiralspulenpaare aus HTS-Material hergestellt ist.
 3. Die NMR-Sonde gemäß Anspruch 1 oder 2, bei der das dielektrische Bauglied (111, 111', 121) für jeden Satz von gegenläufig gewickelten RF-Spiralspulenpaaren ein planares Substrat ist.
 4. Die NMR-Sonde gemäß Anspruch 3, bei der das planare Substrat (111, 121) für jeden Satz der gegenläufig gewickelten RF-Spiralspulenpaare ein Laserlicht blockierendes Material (131, 132, 134) aufweist, das zumindest zwischen Abschnitten des Paares von Spiralspulen von jedem Satz der gegenläufig gewickelten RF-Spiralspulenpaaren angeordnet ist.
 5. Die NMR-Sonde gemäß Anspruch 4, bei der die dielektrischen Bauglieder für beide Sätze von gegenläufig gewickelten RF-Spiralspulenpaare durch ein zylindrisches Bauglied (161) gebildet sind, wobei die Paare von Spiralspulen für beide Sätze von gegenläufig gewickelten RF-Spiralspulenpaaren darauf angeordnet sind, und wobei eine Spiralspule (162) jedes Paares auf einer Außenoberfläche des zylindrischen Bauglieds (161) angeordnet ist, und die andere Spiralspule (172) jedes Paares auf einer Innenoberfläche des zylindrischen Bauglieds (161) angeordnet ist.
 6. Die NMR-Sonde gemäß Anspruch 4, bei der die dielektrischen Bauglieder für beide Sätze von gegenläufig gewickelten RF-Spiralspulenpaare durch ein äußeres und ein inneres koaxiales zylindrisches Bauglied (181, 191) gebildet sind, mit den Paaren von Spiralspulen (182, 192) für beide Sätze von gegenläufig gewickelten RF-Spiralspulenpaaren darauf angeordnet, und wobei eine Spiralspule (182) jedes Paares auf der Außenoberfläche des äußeren zylindrischen Bauglieds (181) angeordnet ist, und die andere Spiralspule (192) jedes Paares auf der Außenoberfläche des inneren zylindrischen Bauglieds (191) angeordnet ist.
 7. Ein Verfahren zum Reduzieren eines elektrischen Felds, das durch ein elektrisches Potential von zwei Sätzen von gegenläufig gewickelten RF-Spiralspulenpaaren (112, 112', 122; 162, 172; 182, 192) einer NMR-Sonde in einer Probenregion induziert wird, und Abstimmen derselben auf eine Resonanzfrequenz einer NMR-Sonde, wobei das Verfahren folgende Schritte aufweist:
 - Bereitstellen von zwei Paaren von gegenläufig gewickelten RF-Spiralspulen (112, 112', 122; 162, 172; 182, 192), wobei die Spiralspulen jedes Paares in entgegengesetzten Winkelrichtungen relativ zueinander gewickelt sind, wenn sich dieselben von einer Innenseite einer jeweiligen Spirale zu ihrer Außenseite bewegen und auf einem dielektrischen Bauglied (111, 111', 121; 161; 181, 191) aufgebracht sind, wobei die Spiralspulen jedes Paares auf gegenüberliegenden Oberflächen des dielektrischen Bauglieds angeordnet sind;
 - Platzieren der Paare von gegenläufig gewickelten Spiralspulen mit der Probenregion zwischen denselben;
 - Treiben der zwei Paare von gegenläufig gewickelten RF-Spiralspulen von einer gemeinsamen Kopplungsschleife (154), wobei der Stromfluss in den vier Spiralspulen der zwei Paare von gegenläufig gewickelten RF-Spiralspulen zu einem bestimmten Zeitpunkt in der gleichen Winkelrichtung ist;
 - Messen des elektrischen Felds in der Probenregion; und
 - Reduzieren des elektrischen Felds durch Einstellen der Länge der Spiralspulen (112, 112', 122; 162, 172; 182, 192) der zwei Paare von gegenläufig gewickelten RF-Spiralspulen.
 8. Das Verfahren gemäß Anspruch 7, das ferner den Schritt des Herstellens jeder der Spiralspulen der zwei Sätze von gegenläufig gewickelten RF-Spiralspulen (112, 112', 122; 162, 172; 182, 192) aus HTS-Material aufweist.
 9. Das Verfahren gemäß Anspruch 7 oder 8, bei dem das dielektrische Bauglied (111, 111') ein planares Substrat ist, das ein Laserlicht blockierendes Material (131, 132, 134) aufweist, zumindest zwischen Abschnitten des Paares von Spiralspulen von jedem Satz der gegenläufig gewickelten RF-Spiralspulenpaare, und jede Spule (112, 112') des Paares von gegenläufig gewickelten Spulen auf gegenüberliegenden Seiten des planaren Substrats befestigt ist.
 10. Das Verfahren gemäß Anspruch 7, 8 oder 9, das ferner den Schritt des Einstellens der Länge von zumindest einer Spiralspule (112, 112', 122; 162, 172; 182, 192) aufweist, durch Schneiden der Spiralspule

unter Verwendung eines Lasertrimmers.

11. Das Verfahren gemäß Anspruch 7, das ferner folgende Schritte aufweist: Herstellen der Spiralspulen (112, 112', 122; 162, 172; 182, 192) aus normalem Metall, und Einstellen der Länge von zumindest einer Spiralspule durch Schneiden der Spirale unter Verwendung eines Skalpells oder eines mechanischen Abschneidewerkzeugs oder eines Lasertrimmers. 5
12. Das Verfahren gemäß Anspruch 7, 8 oder 11, bei dem die dielektrischen Bauglieder für beide Paare von gegenläufig gewickelten RF-Spiralspulen durch ein zylindrisches Bauglied (161) gebildet sind, bei dem auf seiner Außenoberfläche eine Spiralspule (162) jedes Paars angeordnet ist, und auf seiner Innenoberfläche die andere Spiralspule (172) jedes Paars. 10
13. Das Verfahren gemäß Anspruch 7, 8 oder 11, bei dem die dielektrischen Bauglieder für beide Paare von gegenläufig gewickelten RF-Spiralspulen durch ein äußeres und ein inneres koaxiales zylindrisches Bauglied (181, 191) gebildet sind, bei dem eine Spiralspule (182) jedes Paars auf einer Außenoberfläche des äußeren zylindrischen Bauglieds (181) angeordnet ist, und die andere Spiralspule (192) jedes Paars auf der Außenoberfläche des inneren zylindrischen Bauglieds (191) angeordnet ist, wobei die Spulenpaare die Probenregion überspannen. 15 20 25 30

Revendications

1. Sonde RMN incorporant deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires (112, 112', 122; 162, 172; 182, 192) présentant entre elles une région à échantillon destinée à exciter et détecter les signaux RMN d'un échantillon positionné dans la région à échantillon, dans laquelle chaque ensemble desdites paires de bobines en forme de spirale RF enroulées en sens contraires comprend: 35 40
 - une paire de bobines en forme de spirale (112, 112', 122; 162, 172; 182, 192), chaque bobine en forme de spirale étant enroulée dans des directions angulaires opposées l'une par rapport à l'autre lors du déplacement de l'intérieur (113, 123; 163, 173) d'une spirale respective vers son extérieur (114, 124; 164, 174); et 45
 - un élément diélectrique (111, 111', 121; 161, 171; 181, 191) distant desdites bobines en forme de spirale (112, 112', 122; 162, 172; 182, 192), où lesdites bobines en forme de spirale sont déposées sur ledit élément diélectrique et disposées sur des surfaces opposées dudit élément diélectrique, 50 55

dans laquelle une longueur desdites bobines en forme de spirale (112, 112', 122; 162, 172; 182, 192) desdits deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires est ajustée de sorte que soit réduit un champ électrique induit dans la région à échantillon par le potentiel électrique desdites bobines en forme de spirales desdits ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires, et dans laquelle les deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires sont pilotés à partir d'une boucle de couplage commune (154) et le flux de courant dans les quatre bobines en forme de spirale des deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires s'effectue dans la même direction angulaire à un moment donné.

2. Sonde RMN selon la revendication 1, dans laquelle chaque dite bobine en forme de spirale (112, 112', 122; 162, 172; 182, 192) desdits deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires est fabriquée en un matériau HTS.
3. Sonde RMN selon la revendication 1 ou 2, dans laquelle ledit élément diélectrique (111, 111', 121) pour chaque ensemble de paires de bobines en forme de spirale RF enroulées en sens contraires est un substrat plat.
4. Sonde RMN selon la revendication 3, dans laquelle ledit substrat plat (111, 121) pour chaque ensemble de paires de bobines en forme de spirale RF enroulées en sens contraires comprend un matériau bloquant la lumière laser (131, 132, 134) disposé entre au moins des parties de la paire de bobines en forme de spirale de chaque ensemble desdites paires de bobines en forme de spirale RF enroulées en sens contraires.
5. Sonde RMN selon la revendication 4, dans laquelle les éléments diélectriques pour les deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires sont formés par un élément cylindrique (161), avec lesdites paires de bobines en forme de spirale pour les deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires y disposées et dans laquelle une bobine en forme de spirale (162) de chaque dite paire est disposée sur une surface extérieure dudit élément cylindrique (161) et l'autre bobine en forme de spirale (172) de chaque dite paire est disposée sur une surface intérieure dudit élément cylindrique (161).
6. Sonde RMN selon la revendication 4, dans laquelle les éléments diélectriques pour les deux ensembles

de paires de bobines en forme de spirale RF enroulées en sens contraires sont formés par un élément cylindrique coaxial extérieur et un élément cylindrique coaxial intérieur (181, 191) avec lesdites paires de bobines en forme de spirale (182, 192) pour les deux ensembles de paires de bobines en forme de spirale RF enroulées en sens contraires y disposées et dans laquelle une bobine en forme de spirale (182) de chaque dite paire est disposée sur la surface extérieure dudit élément cylindrique extérieur (181) et l'autre bobine en forme de spirale (192) de chaque dite paire est disposée sur la surface extérieure dudit élément cylindrique intérieur (191).

7. Procédé pour réduire un champ électrique induit dans une région à échantillon par le potentiel électrique de deux ensembles de paires de bobines en forme de spirale enroulées en sens contraires (112, 112', 122; 162, 172; 182, 192) d'une sonde RMN et pour les accorder sur une fréquence résonante d'un échantillon RMN, le procédé comprenant les étapes consistant à:

prévoir deux paires de bobines en forme de spirale RF enroulées en sens contraires (112, 112', 122; 162, 172; 182, 192), lesdites bobines en forme de spirale de chaque paire étant enroulées dans des directions angulaires opposées l'une par rapport à l'autre lors du déplacement de l'intérieur d'une spirale respective vers son extérieur et étant déposées sur un élément diélectrique (111, 111', 121; 161, 171; 181, 191), où lesdites bobines en forme de spirale de chaque paire sont disposées sur des surfaces opposées dudit élément diélectrique; placer les paires de bobines en forme de spirale enroulées en sens contraires avec ladite région à échantillon entre elles; piloter les deux paires de bobines en forme de spirale RF enroulées en sens contraires à partir d'une boucle de couplage commune (154), où le flux de courant dans les quatre bobines en forme de spirale des deux paires de bobines en forme de spirale RF enroulées en sens contraires s'effectue dans la même direction angulaire à un moment donné; mesurer le champ électrique dans la région à échantillon; et réduire le champ électrique en ajustant une longueur des bobines en forme de spirale (112, 112', 122; 162, 172; 182, 192) desdites deux paires de bobines en forme de spirale RF enroulées en sens contraires.

8. Procédé selon la revendication 7, comprenant par ailleurs l'étape consistant à fabriquer chaque dite bobine en forme de spirale desdits deux ensembles de bobines en forme de spirale RF enroulées en sens contraires (112, 112', 122; 162, 172; 182, 192) en

un matériau HTS.

9. Procédé selon la revendication 7 ou 8, dans lequel l'élément diélectrique (111, 111') est un substrat plat comprenant un matériau bloquant la lumière laser (131, 132, 134) entre au moins des parties de la paire de bobines en forme de spirale de chaque ensemble desdites paires de bobines en forme de spirale RF enroulées en sens contraire et chaque bobine (112, 112') de la paire de bobines enroulées en sens contraires est montée sur des côtés opposés du substrat plat.
10. Procédé selon la revendication 7, 8 ou 9, comprenant par ailleurs l'étape consistant à ajuster la longueur d'au moins une bobine en forme de spirale (112, 112', 122; 162, 172; 182, 192) en coupant la bobine en forme de spirale à l'aide d'une ébouteuse au laser.
11. Procédé selon la revendication 7, comprenant par ailleurs les étapes consistant à: fabriquer les bobines en forme de spirale (112, 112', 122; 162, 172; 182, 192) en un métal normal, et régler la longueur d'au moins une bobine en forme de spirale en coupant la spirale à l'aide d'un scalpel ou d'un outil de coupe mécanique ou d'une ébouteuse au laser.
12. Procédé selon la revendication 7, 8 ou 11, dans lequel les éléments diélectriques pour les deux paires de bobines en forme de spirale RF enroulées en sens contraires sont formés par un élément cylindrique (161) présentant, disposée sur sa surface extérieure, une bobine en forme de spirale (162) de chaque dite paire et, sur sa surface intérieure, l'autre bobine en forme de spirale (172) de chaque dite paire.
13. Procédé selon la revendication 7, 8 ou 11, dans lequel les éléments diélectriques pour les deux paires de bobines en forme de spirale RF enroulées en sens contraires sont formés par un élément cylindrique coaxial extérieur et un élément cylindrique coaxial intérieur (181, 191) présentant une bobine en forme de spirale (182) de chaque dite paire disposée sur une surface extérieure de l'élément cylindrique extérieur (181) et l'autre bobine en forme de spirale (192) de chaque dite paire disposée sur la surface extérieure de l'élément cylindrique intérieur (191), lesdites paires de bobines enjambant la région à échantillon.

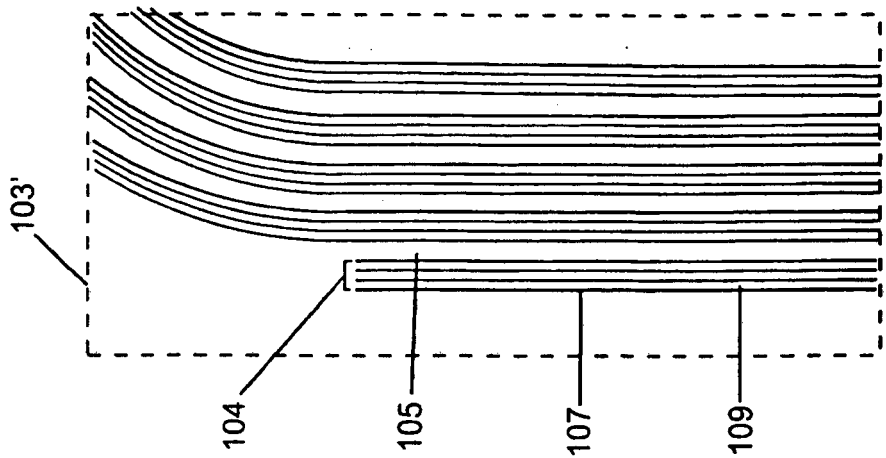


Fig. 1A
(prior art)

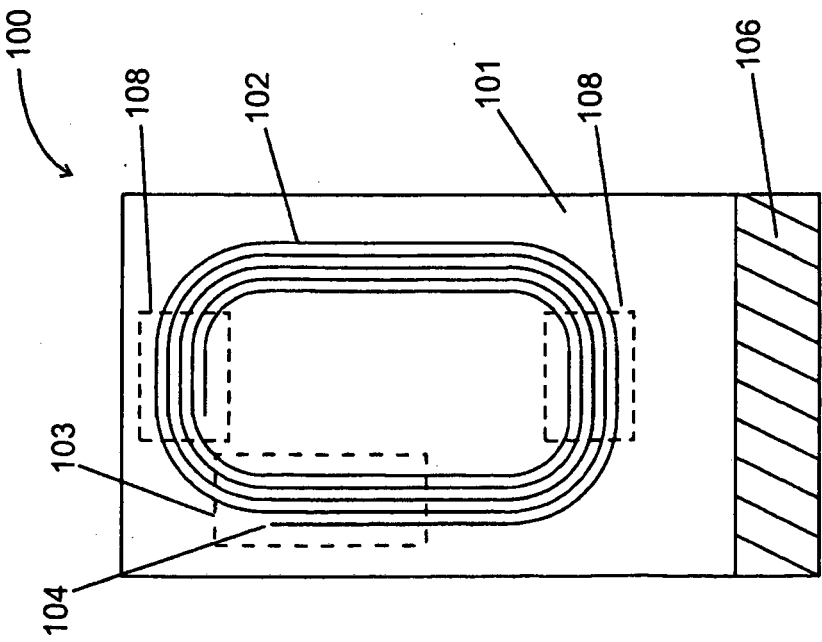


Fig. 1B
(prior art)

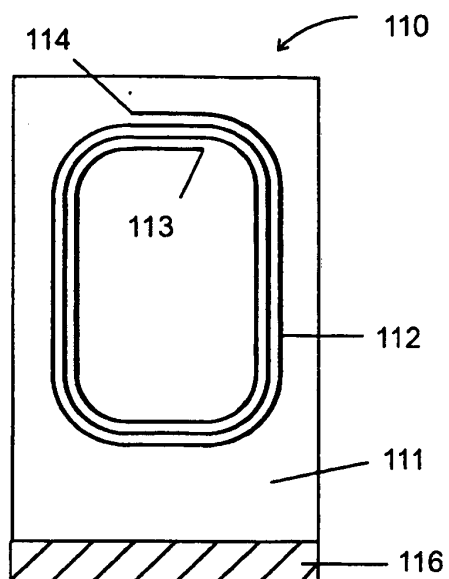


Fig. 2A

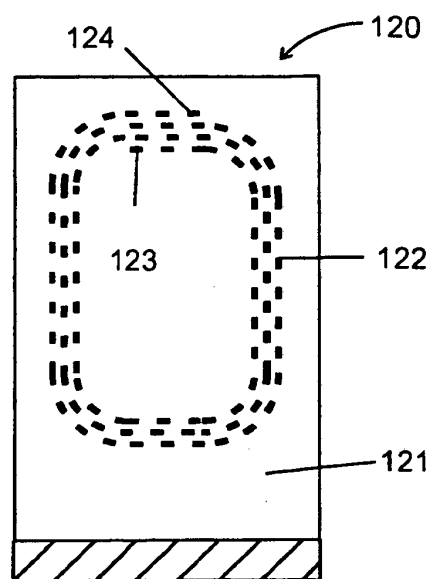


Fig. 2B

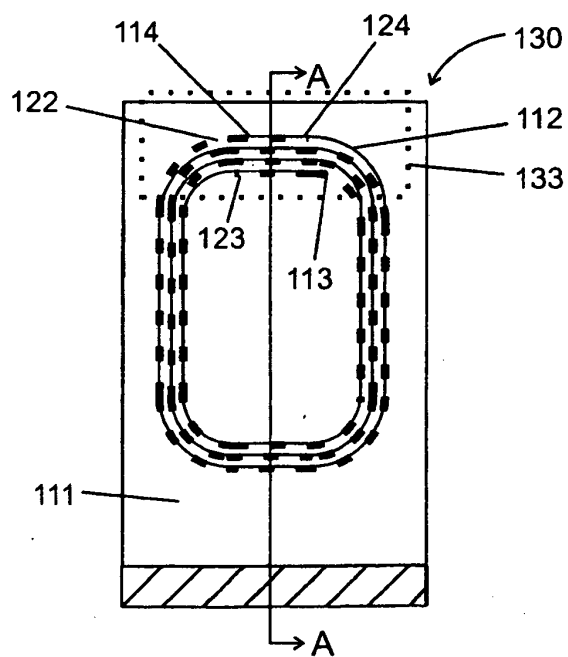
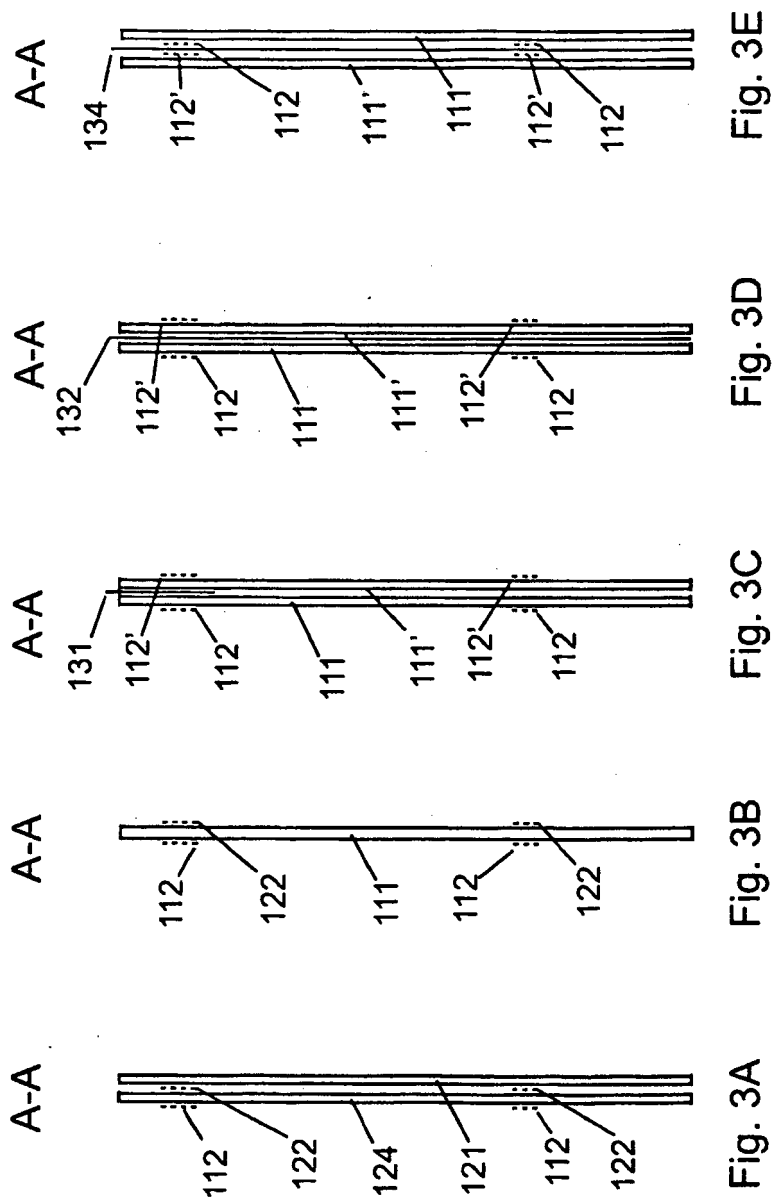


Fig. 2C



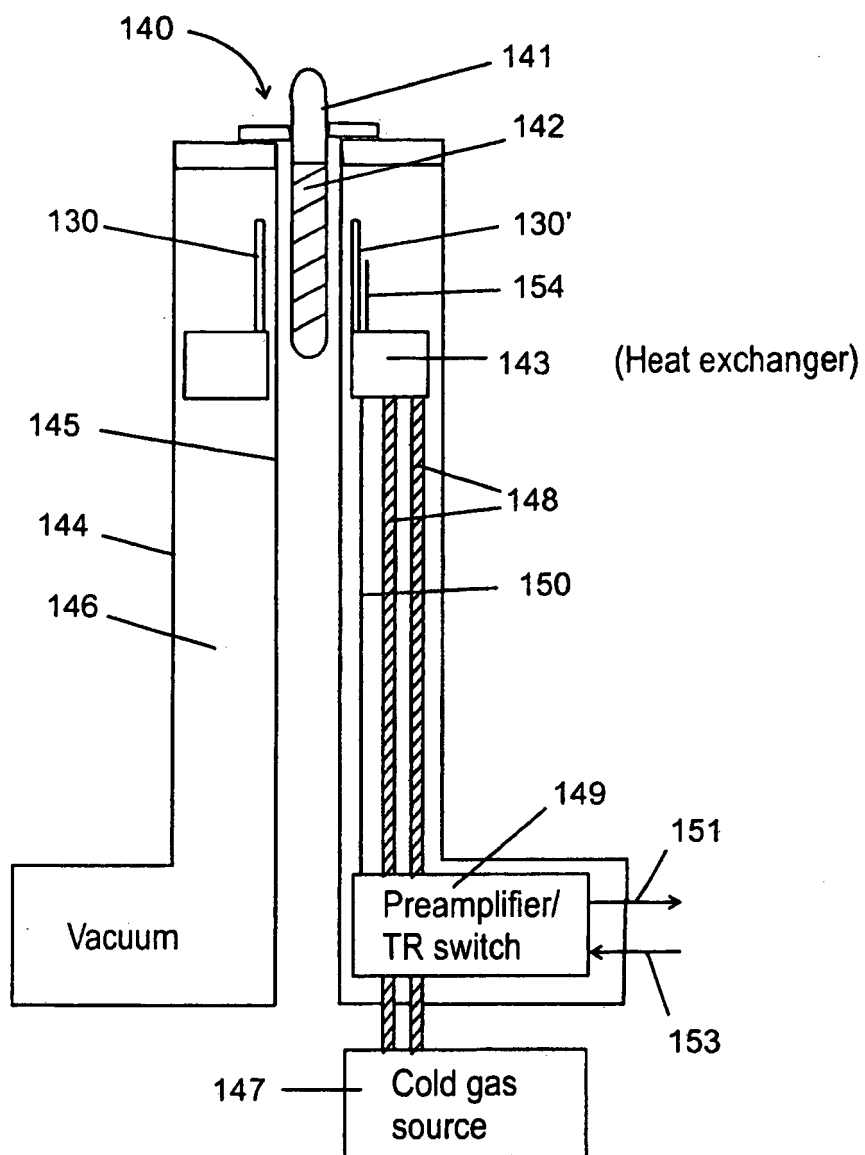


Fig. 4

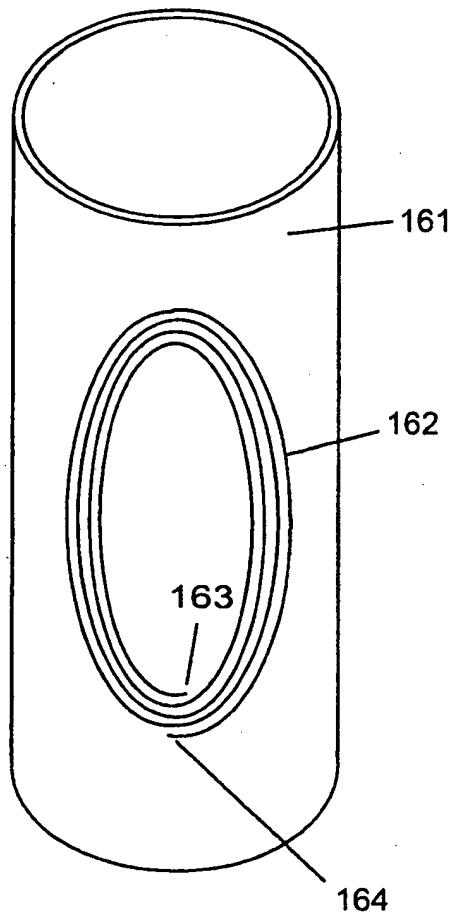


Fig. 5A

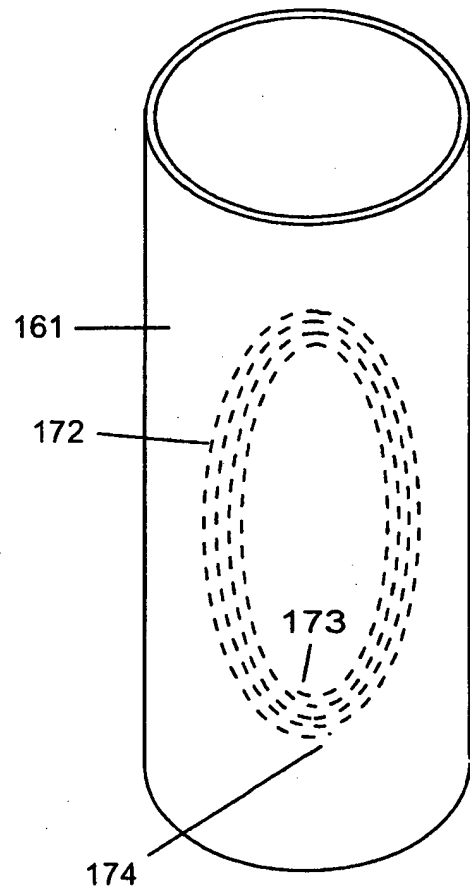


Fig. 5B

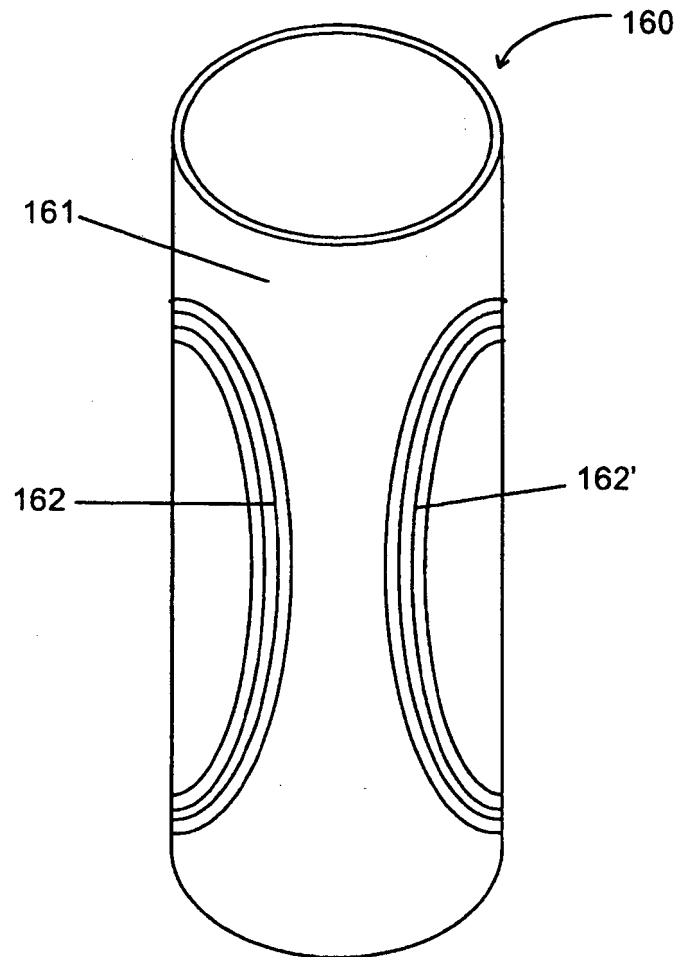


Fig. 6

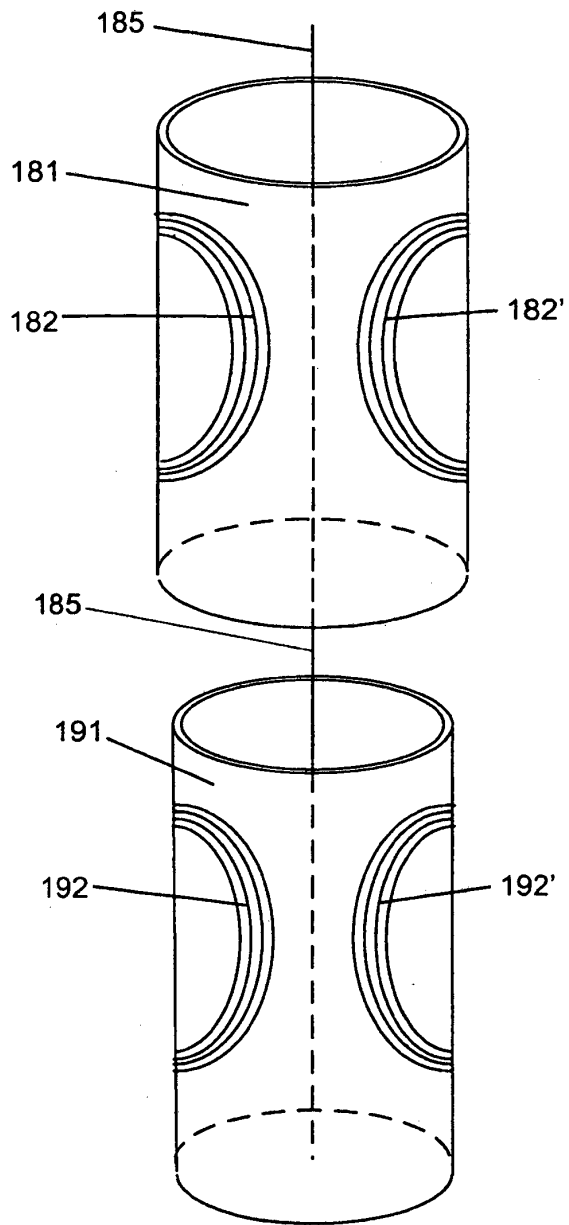


Fig. 7A

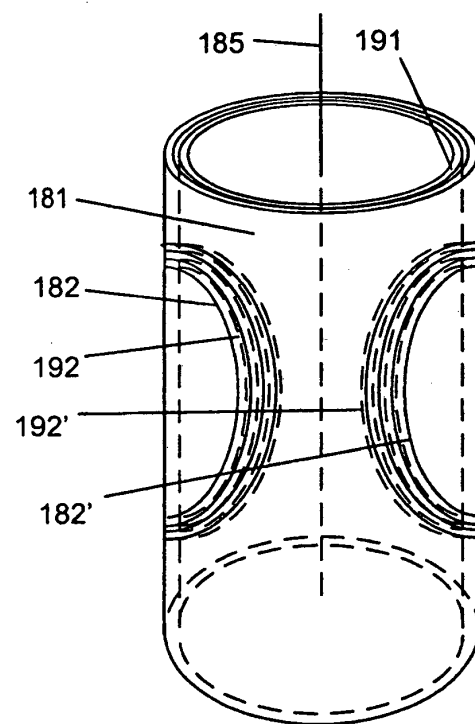


Fig. 7B

REFERENCES CITED IN THE DESCRIPTION

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